



A Summary of the Quasi-Steady Acceleration Environment On-Board STS-94 (MSL-1)

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Abstract

The continuous free-fall state of a low Earth orbit experienced by NASA's Orbiters results in a unique reduced gravity environment. While microgravity science experiments are conducted in this reduced gravity environment, various accelerometer systems measure and record the microgravity acceleration environment for real-time and post-flight correlation with microgravity science data. This overall microgravity acceleration environment is comprised of quasi-steady, oscillatory, and transient contributions.

The First Microgravity Science Laboratory (MSL-1) payload was dedicated to experiments studying various microgravity science disciplines, including combustion, fluid physics, and materials processing. In support of the MSL-1 payload, two systems capable of measuring the quasi-steady acceleration environment were flown: the Orbital Acceleration Research Experiment (OARE) and the Microgravity Measurement Assembly (MMA) system's Accelerometre Spatiale Triaxiale Electrostatique (ASTRE) sensor head. The signature of events such as Orbiter water dumps,

crew activity, and Orbiter attitude changes are most evident in the quasi-steady acceleration regime. Utilizing such quasi-steady events, a comparison and summary of the quasi-steady acceleration environment for STS-94 will be presented.

Acronyms

ASTRE	Accelerometre Spatiale Triaxiale Electrostatique
MMA	Microgravity Measurement Assembly
MSL-1	First Microgravity Science Laboratory
MSP	Microgravity Sensor Package
OARE	Orbital Acceleration Research Experiment
OMS	Orbital Maneuvering System
PAO	Public Affairs Office
QTH	Quasi-Steady Three-Dimensional Histogram
SIMO	Simultaneous Supply Water and Waste Water Dump
STS	Space Transportation System
TMF	Trimmean Filter

Background Information

Introduction

The First Microgravity Science Laboratory (MSL-1) was launched on July 1, 1997 aboard the Space Shuttle Columbia. The MSL-1 payload contained experiments dedicated to studying microgravity sciences, including experiments from combustion, fluid physics, materials processing, and life science disciplines. This successful mission concluded with landing on July 17, 1998.

Accelerometer systems funded or sponsored by the NASA Office of Life Sciences and Applications, Microgravity Research Division are flown on Orbiters to record the microgravity environment. The OARE has flown on numerous Space Shuttle missions, beginning with STS-40. The MMA system's ASTRE sensor flew previously on STS-78, as part of the Life and Microgravity Spacelab (LMS) payload. Throughout the entire MSL-1 mission, the OARE and the MMA system's ASTRE sensor collected low-frequency acceleration data dedicated to measuring the quasi-steady acceleration environment. Measurement of the quasi-steady environment is important in particular to materials science and fluid physics microgravity investigators.

Components of the Quasi-Steady Environment

The quasi-steady acceleration environment is composed of several parts. Three components of the total quasi-steady acceleration environment tend to dominate the overall signal: aerodynamic drag, gravity gradient effects, and Euler or rotational effects. At any point in time throughout a mission, the quasi-steady acceleration environment experienced by a particle in the Orbiter is primarily the collective sum of these three components. The aerodynamic drag component is defined by Equation 1 shown below [1]:

$$A_{aero} = \frac{1}{2} \rho V_a^2 \frac{S_{ref}}{M} C_i$$

where: ρ = atmospheric density
 C_i = body axis aerodynamic coefficient
 V_a = air relative velocity
 M = Orbiter mass (kg)
 S_{ref} = coefficient reference area

Equation 1

As seen from the equation, aerodynamic drag is affected by atmospheric density changes and the body axis aerodynamic coefficient. The

atmospheric density experienced by the Orbiter is primarily a function of Orbiter altitude, solar activity, and diurnal effects. The body axis aerodynamic coefficient is a function of Orbiter attitude or which surface of the Orbiter is in the Orbiter's direction of flight. Gravity gradient effects are a function of the difference in vertical height and horizontal displacement between the Orbiter center of gravity and a location in the Orbiter, such as the OARE or ASTRE sensor locations. Rotational effects result from the centripetal accelerations experienced at an experiment location away from the Orbiter center of gravity as the Orbiter slowly rotates about its center of gravity.

Description Of The Instruments

Orbital Acceleration Research Experiment

The OARE is an accelerometer package managed by the NASA Lewis Research Center in Cleveland, Ohio. This quasi-steady acceleration measurement system is mounted near the Orbiter's center of gravity and contains a triaxial accelerometer that utilizes a free-floating, electrostatically suspended proofmass. The OARE system is controlled by an on-board microprocessor responsible for in-flight experiment control, bias and scale factor calibration, data processing, and data storage. The instrument is capable of measuring accelerations over a range of 10×10^{-9} g to 25×10^{-3} g, with a measurement error of 50×10^{-9} g [1,2]. The OARE sampling rate is 10 samples per second.

Microgravity Measurement Assembly (MMA)

The MMA is a microgravity monitoring system funded and designed by the European Space Agency in The Netherlands (ESA/ESTEC). It is capable of providing microgravity investigators real-time acceleration measurements detected by up to seven sensor heads. These sensor heads consist of up to six Microgravity Sensor Packages (MSP) and one ASTRE sensor. The MSPs are triaxial micromechanical sensors, each with dedicated analog-to-digital electronics. MSPs are capable of measuring acceleration disturbances in the 0.1 to 100 Hz range. These sensors can be located within the Spacelab module, remote from the main MMA system. The triaxial ASTRE sensor is based on the electrostatic suspension of a proofmass and is designed to measure quasi-steady disturbances of frequencies below 2.5 Hz over a range of 10^{-9} to 10^{-3} g [3]. The demonstrated resolution is 1×10^{-9} g with a natural bias of the order of 1×10^{-6} g [4].

The MMA sampling rate is 300 samples per second. The ASTRE sensor is located with the main MMA system.

Data Presentation

Coordinate System

For this paper, data from both the OARE and the ASTRE sensor will be presented in the Orbiter body coordinate system (X_b , Y_b , Z_b) at their respective instrument locations. This Orbiter body coordinate system is shown in Figure 1.

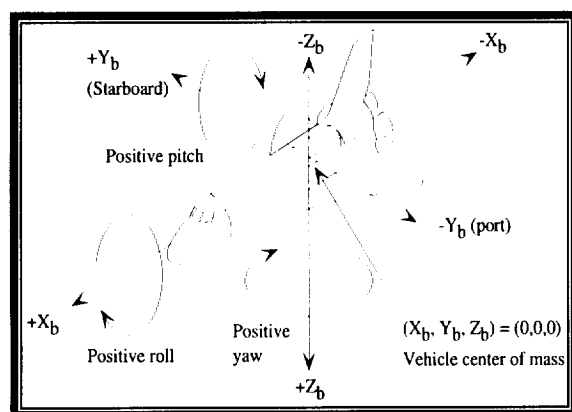


Figure 1 – Orbiter Body Coordinate System

In this coordinate system, the direction from Orbiter tail to Orbiter nose is $+X_b$. The direction from the Orbiter port wing to the Orbiter starboard wing is $+Y_b$. The direction from the top of the fuselage to the Orbiter belly is $+Z_b$. The origin of this coordinate system is at the Orbiter's center of gravity. Data recorded in either the OARE or ASTRE sensor coordinate systems are changed to the Orbiter body coordinate system through a series of orthogonal coordinate transformations [5].

Frame of Reference

For this paper, the sign convention employed for OARE and ASTRE data is with respect to a frame of reference fixed to the Orbiter, meaning a forward thrust of the Orbiter, such as that caused by an OMS burn, is reported as a negative X_b -axis acceleration. In this frame of reference, a free floating particle would appear to translate in the negative X_b -axis direction relative to the Orbiter's acceleration in the positive X_b -axis direction.

Analysis Descriptions

Two plot formats have been used in this paper to analyze the quasi-steady acceleration data recorded by both the ASTRE and the OARE. These plot formats are acceleration versus time format and Quasi-Steady Three-Dimensional Histogram (QTH) format. The acceleration data shown in the acceleration versus time plots are actually filtered representations of the raw, as-recorded acceleration data. This filtering is necessary to extract the quasi-steady accelerations from the raw acceleration data.

For the OARE, the filtering involves the implementation of a trimmean filter (TMF), whose purpose is to adaptively reject transient, higher magnitude accelerations attributable to crew motion and other non-quasi-steady sources. The TMF is performed on the original signal by performing a piecewise estimation of the original data's departure from a purely Gaussian distribution. In addition to extracting the quasi-steady acceleration content in the data, the TMF reduces the OARE data from a raw sampling rate of 10 samples per second to an effective data rate of 1 sample every 25 seconds. A more detailed description of the TMF is available in [6].

The ASTRE data was similarly filtered using a TMF. For the ASTRE data, the TMF reduced the ASTRE data from the raw ASTRE sampling rate of 300 samples per second to a filtered rate of 1 sample every 25 seconds.

The QTH format plot is aimed at summarizing the quasi-steady acceleration vector magnitude and direction for an extended period of time, such as for an entire mission. The measured acceleration vector is projected onto three sets of orthogonal axis pairs: XY, XZ, and YZ. When the tip of the projected acceleration vector falls within one of a number of equally-sized, user-defined two-dimensional acceleration bins, a counter is incremented. This bin size is typically 0.05×10^{-6} g. This process of projecting the acceleration vector onto each of the three sets of orthogonal axes is repeated for the entire data set under analysis. When completed, the number of counts for a particular bin relative to the total number of data points is a representation of the percentage of time the acceleration vector spent at a particular magnitude and direction. A more detailed description of QTH plots can be found in [7,8].

Detailed Analysis

Orbiter Attitude Effects

A summary plot of the OARE data for the entire STS-94 mission is provided in the QTH plot shown in Figure 2. Similarly, a summary plot of the ASTRE data for the entire STS-94 mission is provided in the QTH plot in Figure 3. The MSL-1 mission was flown primarily using two attitudes, $-ZN/55ROLL$ and $-ZN/+XV55ROLL$. These two attitudes are different in that the $-ZN/55ROLL$ attitude, described by the Orbiter body angles [pitch,yaw,roll]=[180, 0, 55], orients the Orbiter's tail in the direction of flight with a +55 degree roll while the $-ZN/+XV55ROLL$ [pitch,yaw,roll]=[0, 0, 235] orients the nose of the Orbiter in the direction of flight with a +235 degree roll.

Ordinarily, two distinct attitudes like these would result in two distinct circular shaped areas of concentration in the QTH plot. However, the similarity in the quasi-steady acceleration for these two attitudes results in the oval shaped clusters observed in Figures 2 and 3. Figure 2 shows that for either of the attitudes flown in support of the MSL-1 mission, the quasi-steady acceleration vector at the OARE location was nominally $(X_b, Y_b, Z_b) = (-0.25 \times 10^{-6}, 0.50 \times 10^{-6}, 0.01 \times 10^{-6})$. Figure 3 shows the nominal quasi-steady acceleration at the MMA ASTRE location was nominally $(X_b, Y_b, Z_b) = (-0.25 \times 10^{-6}, -0.60 \times 10^{-6}, -1.0 \times 10^{-6})$.

Toward the conclusion of STS flights, flight engineers prepare many Orbiter systems for re-entry and landing. For many missions, the Space Shuttle's tires are determined to be in need of warming. This results in maneuvering the Orbiter into a solar inertial attitude, often with the belly of the Orbiter oriented toward the sun. This attitude is referred to as a +ZSI attitude because the positive Z_b -axis (bottom of the Orbiter) is pointed toward the sun. This orbit is maintained for several hours until flight engineers determine the tire temperatures are within their proper range for landing.

The MSL-1 mission required this tire warming, solar inertial attitude. For the MSL-1 mission, the required Orbiter body angles were [pitch,yaw,roll]=[332, 12, 301]. Figure 4 is a plot of OARE data versus time for 4 hours of a solar inertial attitude. Figure 5 is a solar inertial attitude plot utilizing the ASTRE data. Note, the start time for the ASTRE plot (Figure 5) is one hour later than the OARE plot (Figure 4).

The peak-to-peak variations in both plots is primarily attributable to variations in the aerodynamic drag component of the overall quasi-steady acceleration. This variable aerodynamic drag term is caused by variations in the frontal area of the Orbiter presented to the direction of flight: from belly into the velocity vector, to a wing into the velocity vector, to payload bay into the velocity vector, to the other wing into the velocity vector. The larger variations observed in the X_b -axis data (approximately 2.5×10^{-6} g peak-to-peak for both the OARE and ASTRE data) results from the required Orbiter body angles orienting primarily the X_b -axis in the direction of flight.

Orbiter System Effects

The Orbiter Food, Water, and Waste Management Subsystem provides storage and dumping capabilities for potable and waste water [9]. Throughout Orbiter missions, excess supply water and waste water are dumped using nozzles located on the port side of the Orbiter. Figure 6 shows a simultaneous supply water/waste water (SIMO) dump using OARE data. Effects on the quasi-steady acceleration environment are observable in the Y_b -axis and the Z_b -axis. The magnitude of the SIMO dumps is approximately -1.5×10^{-6} g in the Y_b -axis and $+1.8 \times 10^{-6}$ g in the Z_b -axis. The two distinct steps observable during a SIMO dump result from the waste dump portion of these dumps being cycled on and off throughout the duration of the SIMO dump. The supply water portion of the SIMO dump is the lower level of the two distinct steps and is left on continuously through the duration of the dump.

Figure 7 shows a supply water dump alone using ASTRE data. The same port side nozzle of the Orbiter is used to perform the supply water dump. Similar to the SIMO dump effects, the supply water dump has observable quasi-steady acceleration effects in the Y_b -axis and the Z_b -axis. The magnitude of the supply water dumps is approximately -1.5×10^{-6} g in the Y_b -axis and $+1.1 \times 10^{-6}$ g in the Z_b -axis.

Orbiter Crew Effects

As expected, the activity of the crew can affect the quasi-steady acceleration environment. The relative magnitude of the crew's movement within the Orbiter is typically observed when comparing crew sleep/crew awake periods. However, in conducting experiments around the clock, the MSL-1 mission was conducted with two crews with

overlapping sleep and experiment activity periods; no long duration opportunity to observe the crew's effect on the quasi-steady environment exists.

Public Affairs Office (PAO) events are conducted occasionally throughout any shuttle mission. These events are scheduled activities, usually involving the entire crew, used typically for question and answer sessions between the crew and the ground. All the crew members assemble in a common area, such as the flight deck. As a result of the entire crew being co-located and relatively inactive, the normal disturbances from experiment activity and crew movement observed in both the quasi-steady environment and the high-frequency environment are greatly reduced.

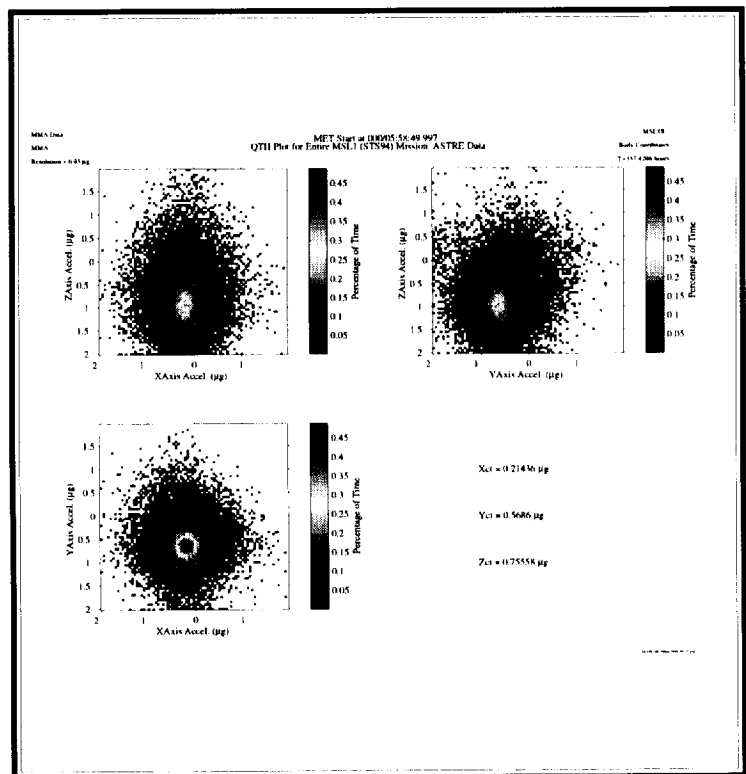
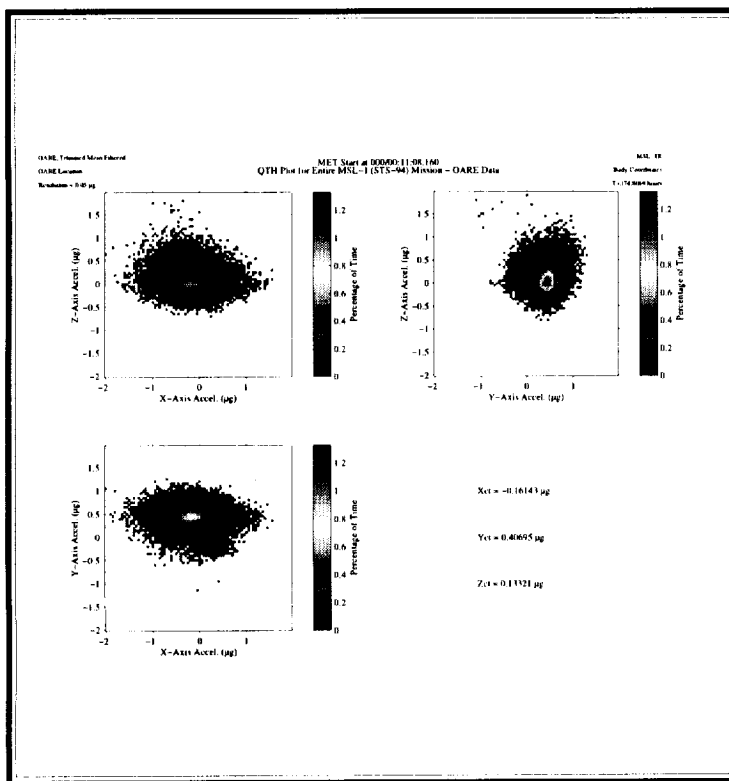
For the MSL-1 mission, at least ten such PAO events were conducted over the course of the mission. Figures 8 and 9 show the effect of a 25 minute PAO event involving the entire crew using OARE data and ASTRE data, respectively. The quieting of the data in the middle of both Figures 8 and 9 is the PAO event. For Figure 8, the peak-to-peak excursions in the OARE data are reduced from a nominal $(X_b, Y_b, Z_b) = (2.0 \times 10^{-6}, 1.0 \times 10^{-6}, 1.2 \times 10^{-6})$ g to 0.2×10^{-6} g for all three axes. For Figure 9, the peak-to-peak excursions in the ASTRE data are reduced from a nominal $(X_b, Y_b, Z_b) = (1.4 \times 10^{-6}, 2.0 \times 10^{-6}, 1.9 \times 10^{-6})$ g to less than 0.5×10^{-6} g for all three axes. These reduced levels are consistent with the reduced levels observed in missions with a single shift, that is where crew sleep periods are readily observed in the measured acceleration environment data.

Summary

The measurement of the quasi-steady acceleration environment during Space Shuttle missions is of particular importance to materials science and fluid physics microgravity investigators. The MSL-1 mission afforded a unique opportunity in measuring the quasi-steady acceleration regime in that two systems, NASA's OARE and ESA's MMA system's ASTRE sensor, were flown with the express purpose of recording the quasi-steady acceleration environment. Both systems successfully demonstrated the ability to measure the nominal quasi-steady acceleration environment and disturbances to that nominal environment that result from Orbiter system and Orbiter crew activity.

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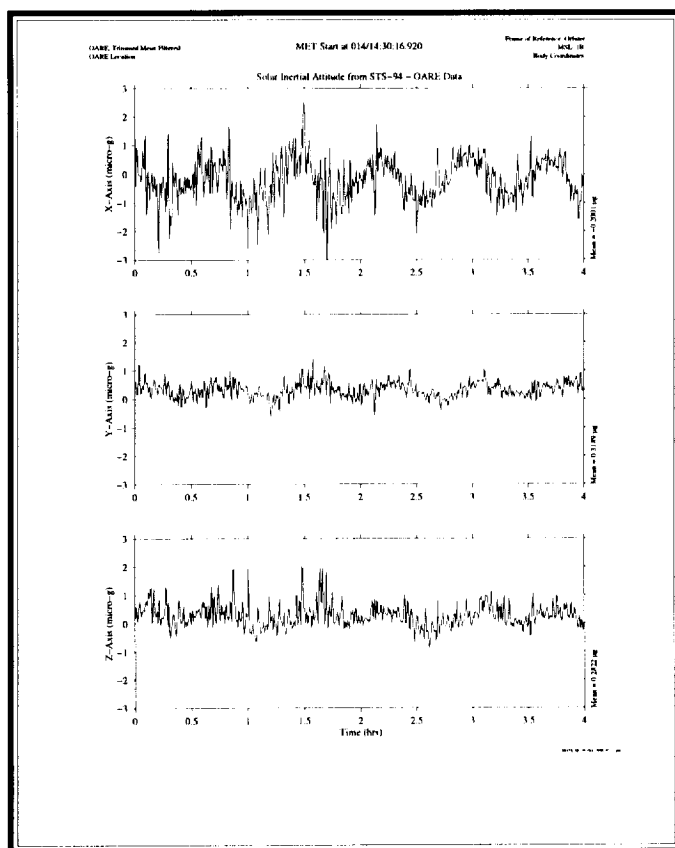
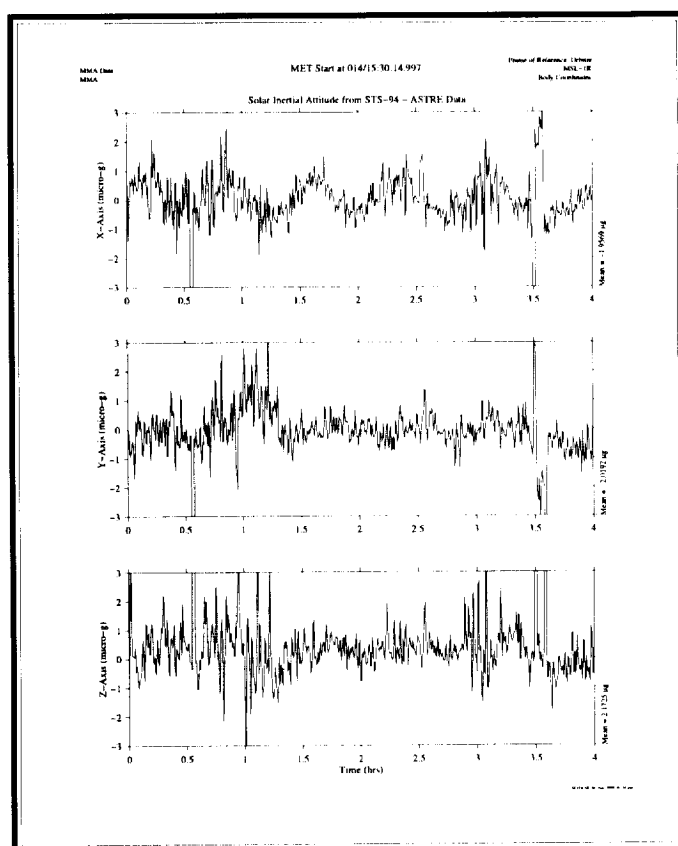


Figure 4 – Solar Inertial Attitude, Acceleration Versus Time Plot for OARE Data

Figure 5 – Solar Inertial Attitude, Acceleration Versus Time Plot for ASTRE Data



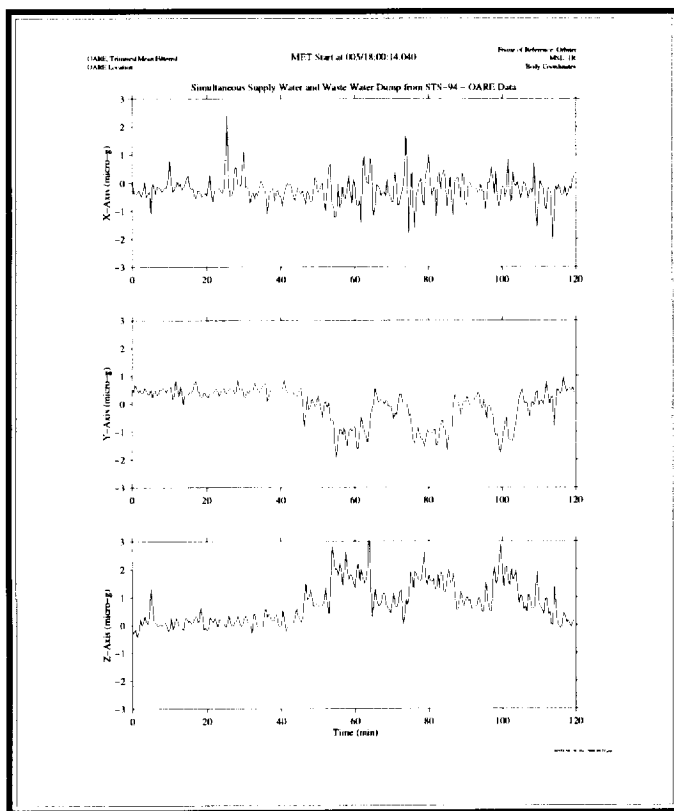
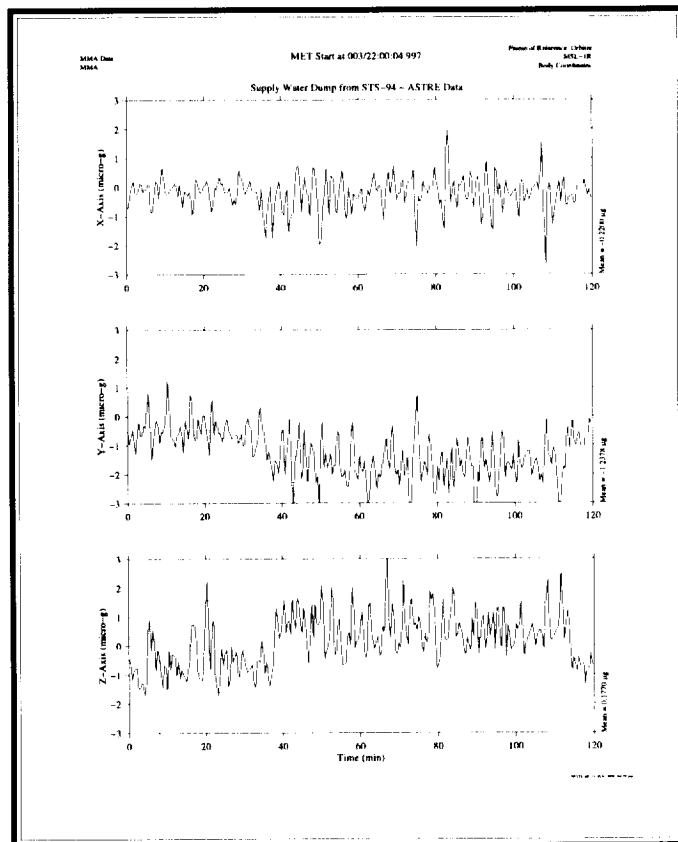


Figure 6 – Simultaneous Supply Water and Waste Water (SIMO) Dump, Acceleration Versus Time Plot for OARE Data

Figure 7 – Supply Water Dump, Acceleration Versus Time Plot for ASTRE Data



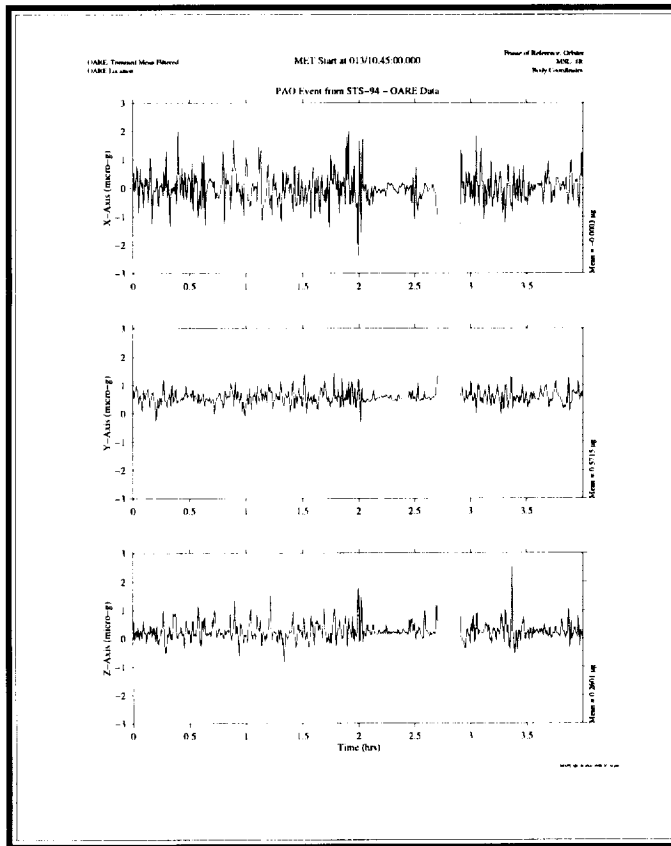
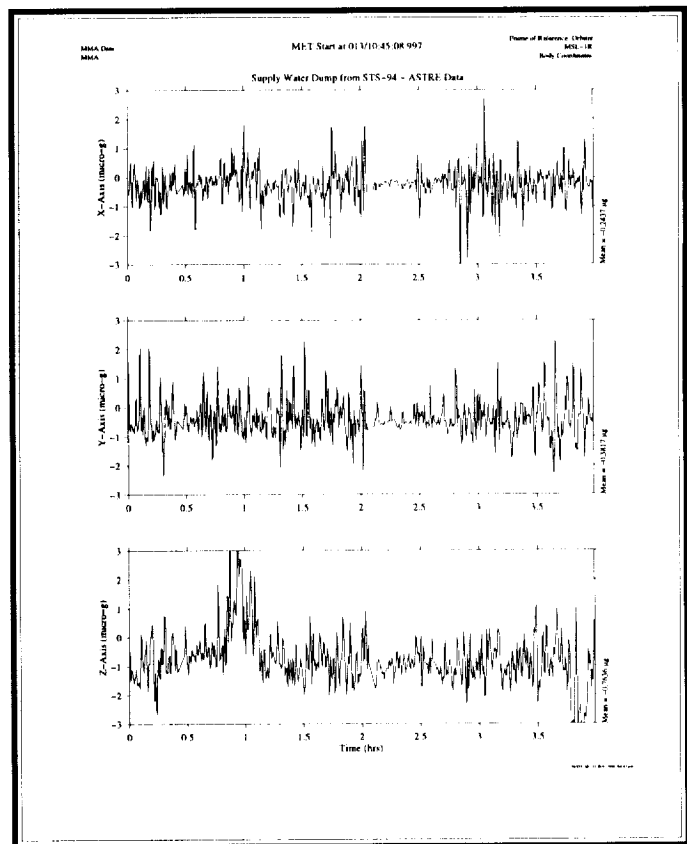


Figure 8 – Public Affairs Office (PAO) Event, Acceleration Versus Time Plot for OARE Data

Figure 9 – Public Affairs Office (PAO) Event, Acceleration Versus Time Plot for ASTRE Data



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